SEARCH FOR AXION-LIKE PARTICLE PRODUCTION IN 400 GeV PROTON-COPPER INTERACTIONS

CHARM Collaboration

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(Submitted to Physics Letters B)

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Numerous scalar states have been predicted [1] characterized as the collective modes accompanying the spontaneous breakdown of symmetries. Among them is the Higgs sector of the standard model and the Peccei-Quinn-Weinberg-Wilczek axion (PQWW-axion) suggested to circumvent P and CP violations in Quantum Chromo Dynamics [2 to 5]. If the axion exists, this would constitute strong evidence in favour of the gauge-theory nature of the fundamental interactions.

The properties of this axion can be calculated in terms of only one free parameter x given by the ratio of the vacuum expectation value of the two Higgs fields as introduced by Peccei and Quinn[2].

The axion mass is given by the following relation [5]:

$$m_a = 25N (x + 1/x) \text{ keV} \quad (1)$$

where N is the number of fermion generations. Weinberg [3] and Bardeen et al. [6] applying current algebra methods deduced a mass of the standard axion in the range of a few hundred keV depending on the value of the various model parameters. The axion mass determines the lifetime of this particle [5]:

$$T(a^0 \rightarrow \gamma\gamma) = 0.7 (100 \text{ keV}/m_a)^5 \text{ sec} \quad (2)$$

The existence of this standard axion has by now been convincingly ruled out experimentally [11,12].

Other axion-like bosons x^0 have been suggested, and as a generic class of particles (such as leptons, quarks) it is important to search for them without reference to any specific theoretical model [7]. If $m_x < 1 \text{ MeV}$, $x^0 \rightarrow \gamma\gamma$ is the only open decay channel with a relatively long lifetime:

$$\frac{\Gamma(x^0 \rightarrow \gamma\gamma)}{\Gamma(\pi^0 \rightarrow \gamma\gamma)} = \left(\frac{F_{\pi^0}}{F_x}\right)^2 \left(\frac{m_x}{m_{\pi^0}}\right)^3 \quad (3)$$

$F_\pi = 94 \text{ MeV}$ [6] is the pion decay constant; the decay constant F_x is a parameter reflecting the mass scale for the dynamics of spontaneous symmetry

breaking. For $1 \text{ MeV} < m_x < 210 \text{ MeV}$, axions decay predominantly into e^+e^- and for $210 \text{ MeV} < m_x < 1 \text{ GeV}$ the dominant decay mode is $x^0 \rightarrow \mu^+\mu^-$. The decay rate in the leptonic channel is given as follows [5]:

$$\Gamma(x^0 \rightarrow \ell^+\ell^-) = \frac{m_\ell^2 (m_x^2 - 4m_\ell^2)^{\frac{1}{2}}}{8\pi F_x^2} \quad (4)$$

with $\ell = e, \mu$.

All decay rates are proportional to F_x^{-2} ; this is also the case for the production cross-section

$$\sigma_x = (F_\pi/F_x)^2 \sigma_{\pi^0} \quad (5)$$

Hence, the sensitivity of searches at accelerators is proportional to F_x^{-4} .

A 400 GeV proton beam was extracted from the CERN-SPS in a single turn (23 μsec) and dumped into a thick copper target. The target was installed at the downstream end of the wide vacuum pipe which serves as decay tunnel for normal beam operations. The distance from the target to the detector was 480 m.

The layout of the decay detector is shown in fig. 1. A scintillation counter hodoscope SCI of $6 \times 4.8 \text{ m}^2$ active area defined the start of the decay volume. The decay region extends over 35 m to a second scintillator hodoscope SC2 of $4 \times 4 \text{ m}^2$ surface area. The decay region was parallel to the neutrino beam line at a mean distance of 5 m, corresponding to an angle with respect to the incident proton beam of 10 mrad.

One module of the CHARM fine-grain calorimeter was displaced to the end of the decay region. This module has an active area of 9 m^2 . The performance of this module is well understood [8] and proven in many experiments. It has been equipped with additional planes of streamer tube chambers [9] to improve the angular resolution of showers. The calorimeter module contains six subunits each consisting of a marble plate of 8 cm thickness ($\sim$ one radiation length) and $3 \times 3 \text{ m}^2$ surface area; a plane of 128 proportional drift tubes, each having dimensions of $3 \times 3 \text{ cm}^2$ in cross section and 4 m length; a plane

of 20 plastic scintillators, oriented at 90° with respect to the proportional tube layer, each 3 cm thick and $15 \times 300 \text{ cm}^2$ in surface area; and a plane of 256 streamer tubes, each having dimensions of $1 \times 1 \text{ cm}^2$ in cross section and 2.6 m in length, oriented parallel to the scintillators. Each marble plane is surrounded by an iron frame.

The decay volume was subdivided into three regions along the 35 metres of its length using two arrays of proportional drift tubes A_1 and A_2 (see fig. 1). These arrays each consisted of four planes of proportional drift tubes preceded by a lead plate of $1/2$ radiation length thickness. The first two planes of each array were aligned horizontally and the last two vertically. The planes were separated by 15 cm.

In order to reconstruct the direction of the showers and the decay vertex with good resolution, we added in front of the CHARM calorimeter module a track detector. This comprised three arrays of proportional drift tubes covering an area of $4 \times 4 \text{ m}^2$. The lead plate of array 3 (see fig. 1) was replaced by a scintillation counter hodoscope of the same area.

The detector was triggered requiring that the veto plane (SC1) was not hit and that at least four elements of the scintillator planes of the calorimeter module were hit.

If axions exist they would be copiously produced by proton interactions with copper nuclei in the beam dump. The axion couples to nucleons like a pion [5], but with a reduced coupling strength so that the production cross section is given by eq.(5).

Axion production was simulated by a Monte Carlo program in analogy to π^0 production [10]. The reliability of the simulation program was checked by comparing the measured average of the primary π^+ and π^- spectra from Be targets [10] assumed to be equal to the π^0 spectrum and the result of the Monte Carlo program. Good agreement is found. For simulation of π^0 production from a thick Cu target effects of the reinteraction of pions in the same nucleus have been explicitly taken into account, as well as the correct material constants for the cascade development in copper. Figure 2 shows the calculated π^0 spectrum including cascade production in the thick copper target. The axion flux was calculated starting with this input and considering the reduced cross

section $(F_{\pi}/F_x)^2$ compared to the π^0 production. The total number of axions we expect in the solid angle covered by the detector is thus:

$$N_x = (F_{\pi}/F_x)^2 \cdot n_{\pi^0} \cdot I_p = (F_{\pi}/F_x)^2 \cdot 2.9 \cdot 10^{17} \quad (6)$$

with $n_{\pi^0} = 1.2 \cdot 10^{-1}$ / int. proton and $I_p = 2.4 \cdot 10^{18}$ protons on target. The mean energy of the π^0 's (and thus of axions) is $E_x = 25$ GeV (see fig. 2).

Candidates of x^0 decays into $\gamma\gamma$, e^+e^- and $\mu^+\mu^-$ have to be selected from a sample of events which is dominated by inelastic scattering of neutrinos and antineutrinos producing hadron showers. We used the regularity of the development of electromagnetic showers as compared to hadronic showers to distinguish between these events.

Because of their regular development and the good tracking properties of the detector, the direction of electromagnetic showers can be reconstructed with good resolution. For electromagnetic showers originating in front of the detector arrays A1 or A2 we find an angular resolution of 1 to 4 mrad in the energy range 5 to 50 GeV. For shower vertices in front of A3 the resolution varies between 4 and 11 mrad, because of the reduced track length.

Hadron showers are wider and have a less regular shape not allowing a precise reconstruction of the shower direction. Two estimators for the separation of electromagnetic and hadron showers have been evaluated using a Monte Carlo simulation: (1) the deviation of the reconstructed shower axis from the incoming beam direction and (2) the fraction of the energy seen in tubes situated outside a narrow cone around the shower axis. Electron and hadron showers were simulated in the energy range 5 to 50 GeV, and their origins were uniformly distributed over the fiducial volume of the decay detector. Figure 3a shows the distributions of the combined estimators (1) and (2) for electrons and for hadron showers of 10 GeV. We note a clear separation. Figure 3b shows the distribution expected for decays of axions with $m_x = 500$ keV, produced with the spectrum in figure 2, and figure 3c shows the distribution of the observed events. No event with an estimator value less than 0.5 is found which would be a candidate for $x^0 \rightarrow \gamma\gamma$ or e^+e^- .

The decay mode $x^0 \rightarrow \mu^+\mu^-$ can be identified with full efficiency by track reconstruction; again, no event candidate was found.

The efficiency for axion decays with an estimator value of less than 0.5 as a function of their mass, of the geometrical acceptance of the detector and of the trigger was calculated using Monte Carlo techniques. For the decay mode $x^0 \rightarrow \gamma\gamma$ and $m_x = 0.5$ GeV the calculated efficiency is 0.51 and for $x^0 \rightarrow \mu^+\mu^-$ the efficiency is 0.85. The 90% confidence limits established in this experiment in a model independent analysis, are shown in figure 4 as a function of m_x and F_x , together with those from previous experiments [11] and from astrophysics [12]. To extend the sensitivity to axions of $m_x > 1$ GeV a shorter distance between the target and the detector would be required to reduce the loss of axions by decay before the detector. Absorption of axions in the shield is negligible as $\sigma_x < \sigma_\pi \cdot 10^{-6}$ in the range of this experiment.

For the special case of the PQWW axion the expected number of decay events as a function of mass is shown in figure 5. The sensitivity to detect PQWW-axion decays peaks for masses between 3 and 5 MeV; it decreases for high masses because of the increasing decay probability before reaching the detector. For an axion of mass $m_a = 250$ keV for which evidence had been claimed [13], we would have expected 15 events in this experiment. As no event was observed we deduce the following limits:

$$\begin{aligned} m_a &< 180 \text{ keV} \\ T_a &> 37 \cdot 10^{-3} \text{ s.} \end{aligned} \tag{7}$$

ACKNOWLEDGEMENT

We would like to thank J.D. Bjorken and R.P. Peccei for fruitful discussions on the theoretical aspects of scalar particles, and to express our gratitude and appreciation to our numerous technical collaborators who contributed to the construction of the special decay detector. The efficient help of J. Audier and C. Busi with data handling is gratefully acknowledged.

REFERENCES

1. L.B. Okun, Proceedings of the International Symposium on Lepton and Photon Interactions at High Energies, Phys. Inst., Univ. Bonn (1981) page 1018.
2. R.P. Peccei and H.R. Quinn, CP Conservation in presence of pseudoparticles, Phys. Rev. Lett. 38 (1977) 1440.
3. S. Weinberg, A new light boson? Phys. Rev. Lett. 40 (1978) 223.
4. F. Wilczek, Problem of strong P and T invariance in the presence of instantons, Phys. Rev. Lett. 40 (1978) 279.
5. T.W. Donnelly et al., Do axions exist?, Phys. Rev. D18 (1978) 1607.
6. A. Bardeen, S.H. Tye, Current algebra applied to properties of the light Higgs boson, Phys. Lett. 74B (1978) 229, and
A. Bardeen et al., Phys. Lett. 76B (1978) 580.
7. See also J.D. Bjorken and L.W. Mo, Proposal E695 FNAL.
8. M. Jonker et al., CHARM Collaboration, The response and resolution of a fine-grain marble calorimeter for hadron and electromagnetic showers, Nucl. Inst. Meth. 200 (1982) 183.
9. M. Jonker et al., CHARM Collaboration, The limited streamer tube system of the CHARM Collaboration, Nucl. Inst. Meth. 215 (1983) 361.
10. H. Atherton et al., Precise measurements of particle production by 400 GeV/c protons on beryllium targets, CERN 80-07 (1980).
11. C. Edwards et al., Upper limit for $J/\psi \rightarrow \gamma + \text{axion}$, Phys. Rev. Lett. 48 (1982) 903.
M.S. Alam et al., Search for axion production in T decay, Phys. Rev. D27 (1983) 1665.
B. Niczyporuk et al., Experimental upper limits for hadronic and axion decays of the T(1S), Z. Phys. C17 (1983) 197.

- M. Sivertz et al., Upper limit for axion production in radiative T decay, Phys. Rev. D26 (1982) 717.
- J. Bjorken, Search for neutral penetrating, metastable particles in the SLAC Beam Dump. Rencontre de Moriond (1984), 227.
- J.S. Frank et al., New experimental limit on the muon-neutrino lifetime, Phys. Rev. D24 (1981), 2001.
12. Astrophysical limits, J.D. Bjorken, private communication.
13. H. Faissner et al., Observation of the two-photon decay of a light penetrating particle, Phys. Lett. 108B (1981) 234.

FIGURE CAPTIONS

Fig. 1 Layout of the decay detector with a decay region of 35 m length and a 9 m² surface area. SC1 is veto scintillator plane and SC2 is a scintillator hodoscope. A1 to A5 are arrays of 4 planes of proportional drift tubes. The calorimeter module is 6 radiation lengths deep. Lead converters for γ rays of $1/2 X^0$ each were placed in front of A1, A2, A4 and A5.

Fig. 2 Spectrum of π^0 produced in 400 GeV proton interactions on copper beam dump at a mean angle of 10 mrad (Monte Carlo simulation).

Fig. 3a Estimator for the separation of 10 GeV electron and pion showers.

Fig. 3b Estimator distribution for decays $X^0 \rightarrow 2\gamma$ of axions with $m_X = 500$ keV produced in the target and for hadrons with the observed energy spectrum.

Fig. 3c Estimator distribution of observed events.

Fig. 4 Limits on m_X and on the decay constant F_X for axion-like bosons as a generic class of particles established at the 90% confidence level by this and by other experiments [11] and by astrophysical [12] considerations.

Fig. 5 Number of decays of PQWW axions expected in this experiment as a function of their mass. For $m_a = 250$ keV 15 events would be expected [13] and none was observed.

Fig.1

Fig.2

Fig.3

Fig.4

Fig.5